JOURNAL OF•BALTIC SCIENCE EDUCATION

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

MULTIMODAL REPRESENTATIONS FOR DEVELOPING PRESERVICE TEACHERS´ SYSTEMS THINKING FOR ADDRESSING COMPLEX HEALTH ISSUES

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Abstract. *Science educators highlight the importance and difficulty of developing systems thinking (ST) for addressing complex health problems such as antimicrobial resistance (AMR). Thus, it is necessary to study which strategies can facilitate this development. This study addressed how modelling activities fostered the ST developed by pre-service teachers (PSTs) in the context of AMR. The identification of components and relationships, the proposal of actions, and taking an 'inside the system' perspective were considered as ST dimensions. The research data consisted of explanations about AMR written individually at the beginning and at the end of the sequence, as well as group activities, performed by a group of 56 PSTs. The results show that after completing the activities, most participants explained AMR including 'One Health' vision, saw themselves as victims of AMR but less as causes or agents of change, and articulated complex cause-effect relationships in their retrospective reasoning. Moreover, the performance of retrospective reasoning in intermediate activities that implied diverse representations stood out. It was concluded that using multimodal representations might be a useful strategy in science education to facilitate the development of PSTs´ ST for understanding and acting on systems.*

Keywords: *antimicrobial resistance, mixed methods, model representation, preservice teachers, systems thinking*

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Introduction

The aim of education is to prepare students to act on socioscientific problems and contribute to the building of a fairer, more equitable, and sustainable world. To this end, science education has the potential to contribute to the development of knowledge and skills, training scientifically competent students capable of understanding the complex systems involved in socioscientific problems, and of acting critically and responsibly on them. Identifying the ways in which science education can achieve this is the goal of researchers in the field. One challenge of science education is to prepare students to face current and future problems (Organisation for Economic Co-operation and Development [OECD], 2018). One of such health problems is antimicrobial resistance (AMR), a natural phenomenon exacerbated by human actions. It is estimated that AMR was directly responsible for 1.27 million deaths globally in 2019, contributing to 4.95 million deaths that same year (Antimicrobial Resistance Collaborators, 2022), and that this figure could double by 2050 (United Nations Environment Programme [UNEP], 2023). The European Centre for Disease Prevention and Control [ECDC] publishes an annual report on the incidence of resistance in different pathogens to various antimicrobials in European countries. It is estimated that since 2020, 35,000 people have died each year as a direct result of antimicrobial-resistant infections, and according to the 2024 report (ECDC, 2025), although there has been a slight change in trend for some pathogens, for most, AMR continues to increase, and the targets set for 2030 are not expected to be met.

AMR is a problem to be addressed from a global perspective, taking into account the various and complex interrelationships between organisms (O'Neill, 2016; UNEP 2023; World Health Organisation [WHO], 2023), since, for example, the use of antimicrobials in agriculture and livestock farming contributes to the worsening of AMR. This comprehensive approach to health is called One Health (OH) (Food and Agriculture Organisation of the United Nations [FAO] et al., 2019) and is based on the consideration that the health

https://doi.org/10.33225/jbse/26.25.409

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

of humans, domestic and wild animals, and the environment in general (including plants and ecosystems) are closely linked and interdependent. Traditional approaches considered animal health issues in isolation from human health. However, episodes resulting from zoonoses as the COVID-19 pandemic and other health issues such as AMR highlight the close relationship not only between human and animal health but also between these and ecosystems, and therefore the need for global approaches.

The seriousness of the problem led the WHO to propose to 'develop age-appropriate curricula on AMR for primary and secondary schools' (WHO, 2023, p.14). This involves, among other things, addressing some concepts that people of various ages have shown difficulty understanding. On the one hand, knowledge about antimicrobials and their use (European Union, 2022), partially linked to the common confusion between viruses and bacteria. In the context of AMR, a specific difficulty is that many people do not even associate it with the aforementioned microorganisms, but rather believe that it is the human body that becomes resistant (i.e., Martínez-Pena et al., 2024; Shahpawee et al., 2020). Among those who do associate it with microorganisms, difficulties have been found in understanding the mechanisms of AMR generation and the role of antimicrobials in it (Martínez-Pena et al., 2024; Peel et al., 2019; Shahpawee et al., 2020). Finally, the OH vision mentioned above as necessary to address AMR (O'Neill, 2016; UNEP 2023; WHO, 2023) is not often considered, as has been found in the few studies that have attempted to examine it (Martínez-Pena et al., 2024; Drymiotou et al., 2025). Developing this more complex and global vision requires developing systemic thinking (ST) skills, so that students are able to identify the different elements that form part of the problem and how they relate to each other to generate it (Ben-Zvi-Assaraf & Orion, 2005; Hmelo-Silver et al., 2017). ST is a highly demanding cognitive skill that is key to science education (NGSS Lead States, 2013; OECD, 2023). However, few studies have addressed its development in preservice or inservice teachers (Bielik et al., 2023a; Budak & Ceyhan, 2024), who are the agents necessary to design and implement activities for the development of ST in students of different ages.

This work addressed how a modelling sequence, a strategy used to develop the ST (i.e., Bielik et al., 2023b), enables preservice teachers (PSTs) to develop knowledge about the phenomenon under consideration, in this case AMR from a global perspective, so that they can identify the different elements involved and their interrelationships. More specifically, modelling involves representing the system in various ways that can be evaluated and revised and that can be used to make predictions. In this work, it was analysed how these various representations contribute to the development of ST and knowledge about a complex phenomenon.

AMR in Education Settings

AMR has been used as a context for developing and assessing students' knowledge of natural selection, mutations, and evolution (Kilstadius & Gericke, 2017). The participating experts in the Delphi study conducted by Kilstadius and Gericke (2017) complained that AMR was not being taught in relation to infectious diseases and that, in education, it was addressed only to understand evolutionary mechanisms.

Indeed, in secondary education, for example, Peel et al. (2019) carried out activities with several modelling cycles that included virtual simulations to work on the concepts involved in natural selection and the generation of AMR with 10th grade students. Along the same lines, Bohlin et al. (2018) used AMR animations with 13-14-year-old students, as 15-year-old students had shown difficulties with this concept in tests conducted in Sweden. Animations have also been used to help students overcome the idea that mutations originate in response to the environment (Wanford et al., 2018), i.e., to antibiotics. Several collaborative experiences have also been developed within the framework of service learning (Kupis et al., 2025; Robredo et al., 2023) or open schooling (Drymiotou et al., 2025) between secondary school students and university students and/or AMR experts with the aim of developing knowledge about AMR.

Although the aforementioned studies have addressed issues to be taken into account in teaching AMR and, in some cases, have dealt with OH problems tangentially, the latter has not been given the weight it deserves. In fact, in a systematic review of the literature conducted on 144 studies that analysed health students' knowledge of antimicrobials (Alzard et al., 2024), the authors concluded that the evaluation in the studies addressed the administration of antimicrobials in a rather superficial manner and that there was a need to develop knowledge about other factors that contribute to AMR, such as the relationship with ecosystems and animals, and OH vision. Marvasi et al. (2021) conducted a review of activities that addressed AMR with different audiences from an OH perspective. However, the OH approach was not the focus; rather, as the researchers pointed out, the focus was on the misuse of antibiotics in humans.

https://doi.org/10.33225/jbse/26.25.409

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Robredo and colleagues have included a more global perspective, although they have not focused on it. For example, Robredo and Torres (2021) included three questions in their questionnaire on different aspects related to microorganisms, the use of antibiotics, and AMR, related to the transmission of resistant bacteria. Robredo et al. (2023) carried out a service-learning project with university and secondary school students that involved collecting soil samples to identify bacteria capable of producing potentially antimicrobial molecules. Although, as in the previous case, the project did not include the development of the students' concept of OH among its objectives, the context they proposed for studying the problem of AMR (the soil) connects the human and environmental dimensions that form part of the concept of OH. In their open schooling project, Drymiotou et al. (2025) also included an OH module, which students found 'fascinating, as it introduced them to the impact of AMR on the environment, animals, and plants, an entirely new concept for them' (p. 14). However, they did not analyse the degree of learning around this topic.

Using Representations to Develop Systemic Thinking

Developing an ST approach requires, among other basic characteristics of ST, to identify the parts or elements that make up the system, identify and understand the interactions that occur between them, and the phenomena to which they give rise (Ben-Zvi-Assaraf & Orion, 2005). ST facilitates the holistic approach to complex problems and is therefore important in science education (Ben-Zvi-Assaraf & Knippels, 2022), which explains its presence in documents that guide teaching in different countries. Thus, Systems and System Models is a crosscutting concept (NGSS Lead States, 2013), and the OECD recognises the relevance of ST for the development of scientific competence (OECD, 2023). Although there are different definitions and conceptions of ST, many converge on some of its characteristics. In this paper, ST is considered a competence that requires identifying the elements that are part of a system, as well as the relationships between them (e.g., Ben-Zvi-Assaraf & Orion, 2005; Hmelo-Silver et al., 2017; Hmelo-Silver & Pfeffer, 2004; Mehren et al., 2018; Snapir et al., 2017), establishing cause-effect networks and identifying non-linear relationships and feedback loops (Ben-Zvi-Assaraf & Orion, 2005; Hipkins, 2021; Mehren et al., 2018), thinking about emerging phenomena (Ben-Zvi-Assaraf & Orion, 2005; Hipkins, 2021), taking an 'inside the system' perspective (Hipkins, 2021), and anticipating system dynamics decide how to act within the system (Hipkins, 2021; Mehren et al., 2018; Ossimitz, 2000). To characterise such ST, the work of Mehren et al. (2018), who empirically validated a model for ST competency for addressing environmental systems, has been considered. The model consisted of one retrospective dimension (ST-OrgBeh) related to understanding the system (components and relationships), and a prospective dimension (ST-Action) that includes the formulation of actions.

Teachers are undoubtedly key agents in implementing activities for the development of ST in educational practice; to do so, teachers must have developed this ability themselves. However, the few studies that have addressed this issue reveal considerable shortcomings. As reflected in two reviews of ST studies, few address its development in preservice or in-service teachers (Bielik et al., 2023a; Budak & Ceyhan, 2024). The results of these studies point to the need to work on the development of ST in teachers. Hmelo-Silver and Pfeffer (2004) analysed the structure, behaviour, and functions identified by 11th-grade students, PSTs, and experts in the field. They found that ST of PSTs did not differ from that of students, but it did differ from that of experts, in that PSTs and students focused on structural representation and had more difficulty identifying behaviours and functions, which, on the contrary, constituted the principles of organisation of system understanding for experts. The PSTs in the study by Palmberg et al. (2017) also showed large deficiencies in ST: three quarters of the 424 PSTs showed no evidence of ST when relating species identification, biodiversity, and sustainable development. Karga and Ceyhan (2026) and Gilissen et al. (2020) detected deficiencies in ST in science teachers. For example, Gilissen et al. (2020) compared how ST was being implemented in biology teaching in the Netherlands with experts' vision and concluded that teacher training should enable teachers to understand the characteristics of biological systems and highlight the role of modelling in the development of ST.

In fact, the role of modelling, that is, the representation of the system for its use, evaluation, and revision (Schwarz et al., 2009), has been highlighted by several researchers who have addressed the issue of how to facilitate the development of ST in students (Bielik et al., 2023b; Hmelo-Silver et al., 2017). Of the five types of models or representations described by Gilbert (2005), the visual mode includes drawings, diagrams, and simulations performed in virtual environments. The latter, *NetLogo*, *HubNet,* and others (Stroup & Wilensky, 2014) have been widely used for studying system dynamics, for simulating ecosystems, and the spreading of diseases, among others. Similar simulations were used by Eidin et al. (2024) to develop secondary school students' causal and temporal reasoning in a chemistry topic, yielding some positive results, although the students continued to demonstrate relatively linear

https://doi.org/10.33225/jbse/26.25.409

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

causal reasoning. Other visual representations, such as drawings, diagrams, and material models, are also widely used and effective in promoting deep reflection on the model, facilitating learning in science (Prain & Tytler, 2012; Tytler et al., 2023). In the context of promoting ST, concept maps and mind maps have been used, among others (e.g., Hmelo-Silver et al., 2017; Tripto et al., 2013, 2017; Uskola & Puig, 2023). For instance, Tripto and colleagues examined how students employed ST when addressing homeostasis (Tripto et al., 2013) and the human body system (Tripto et al., 2017) through concept maps. Hmelo-Silver et al. (2017) went further and analysed how creating concept maps of ecosystems in a virtual environment helped students better understand ecosystem dynamics than those who used traditional methodology, enabling them to identify more components and mechanisms. In the study by Uskola and Puig (2023), students created mind maps on the emergence of epidemics from an OH perspective. The researchers concluded that making mind maps acted as a necessary, but not sufficient, condition, as only groups that had constructed a map with links between chains or feedback loops were able to show these elements in subsequent group activities; nevertheless, they did not report individual results.

Research Aim and Research Questions

In light of the recognized importance of fostering ST in the general population (and especially among PSTs) and acknowledging the difficulties involved in its development, this study sought to identify educational activities and strategies that could support its development. Specifically, this research examined the contribution of modelling activities that included the multimodal representation of the system to promote the development of PSTs' ST, enabling them to understand a global, live, and worrying health problem, such as AMR, in a complex way and take action. Specifically, it addressed the following research questions:

RQ1. How do PSTs´ ST in understanding AMR evolve when they participate in a modelling sequence of activities?

RQ2. How do the various modelling activities contribute to the development of ST dimensions?

Research Methodology

General Background

The research was mainly based on the interpretative analysis (LeCompte et al., 1992) of qualitative data (written productions and mind maps made by PSTs). The participants were chosen for convenience, one researcher being their teacher in the 2024/25 academic year, when the data collection was carried out. Thus, the research was a teacher-research (Roth, 2007) that required specific conditions by the Ethics Committee for Research with Human Beings, Samples and Data at the University of the Basque Country (UPV/EHU) that approved the project (M10_2021_161) that included this study. It was explored how the various representations of a system throughout a modelling sequence facilitated the development of ST in a group of PSTs, in the context of a complex health problem, AMR. These representations, consisting of individual written explanations, group-written work, and group mind maps, were analysed as the data. Researchers searched for occurrences of the dimensions related to ST, adapting them from Mehren et al. (2018). Therefore, a mixed-methods research methodology was used (Creswell, 2012): the data were qualitative, the interpretative analysis was qualitative, and the subsequent statistical analysis was quantitative.

Participants

The participants in the study were students enrolled in the Primary Education Degree programme at the University of the Basque Country (UPV/EHU). Specifically, there were 56 PSTs (35 women and 21 men) with an average age of 21, chosen for convenience, who took a 4th-year elective course on innovative perspectives in science teaching in the 2024/25 academic year. All participants gave informed consent to participate in the research. The previous knowledge on the topic of AMR was scarce. Across the three previous academic years, one of the subjects focused on Biology education, where the knowledge about bacteria was covered at a level similar to basic education (type and characteristics of living beings). Throughout the sequence, PSTs worked in 12 groups with 4-5 members. In the data collection process, groups were coded as G1-G12 and PSTs as PSTx.y, where x was the number of the group and y the number of the member in that group.

https://doi.org/10.33225/jbse/26.25.409

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Teaching Sequence

The sequence of activities is described in Table 1. All activities took place in the classroom. After responding to an individual questionnaire on AMR (A1-i), activities A2-g to A4-w aimed to construct an appropriate model of how AMR is generated. To do this, they worked in groups on the ideas they had written down in the questionnaire, first without access to extra information, and then with access to information via the internet. The teacher did not limit their search. Each group wrote and drew a final explanation, then one of the groups presented its explanation, and the teacher asked questions about each step of the process until a complete explanation was reached. In a subsequent session, with the aim of broadening their vision and integrating OH approach, PSTs were provided with various documents (https://doi.org/10.6084/m9.figshare.31069501). Each participant read one or two documents and shared the information. As the interrelationships between the components are difficult to consider for students, scaffolding is needed (Ben-Zvi-Assaraf & Knippels, 2022). In this case, this was done through an appropriate question (Zamalloa et al., 2023). Given that previously (Uskola et al., 2024), it was observed that the mind maps were more complete when the guideline 'represent all the possibilities by which I may encounter AMR' was given than when the formulation was more general, this was the guideline given to groups to list the ways in which the problem arises (A6-g). This list served as a starting point for developing the mind maps (A7-g). Mind maps are visual representations that comprise a network of connected concepts, and unlike concept maps, mind maps do not show relational words or phrases to aid understanding of relationships (Davies, 2011). After developing the mind map, each group proposed three actions that could help minimise the problem (A9-g). Then they are asked to make a video focused on one of the proposed actions, with the aim of helping them take ownership of both the problem and the proposed actions to address it. However, the videos produced, lasting between 2.5 and 5 minutes, suggested that the guidelines given for their production and focus had not been sufficiently clear or appropriate, as some of them did not even mention the problem of AMR. For this reason, the videos were not taken into account in this study. Finally, they answered the same questionnaire as at the beginning (A11-i).

Table 1
Activities in the Modelling Sequence

Session	Activity	Description
1 (120 min., 23 October 2024)	A1-i	Initial questionnaire
	A2-g	Group discussion without extra information
	A3-g	Group discussion with extra information
	A4-w	Sharing and joint explanation on the whiteboard
2 (150 min., 23 October 2024)	A5-i	Reading texts
	A6-g	Group summary statements
	A7-g	Elaboration of mind map
	A8-g	Emerging statements
3 (80 min., 6 November 2024)	A9-g	Actions
Out of class	A10-g	Video
4 (60 min., 20 November 2024)	A11-i	Final questionnaire

Note. min.: minutes; i: individual activity, g: group activity, w: whole class activity.

Instruments and Data Analysis

The analysis was conducted adapting the ST dimensions defined by Mehren et al. (2018), as displayed in Table 2. ST-Comp addresses components of the system (Hmelo-Silver et al., 2017) and corresponds to references to the three dimensions (human, environmental, and animal) of OH notion (FAO et al., 2019). ST-OrgBeh addresses the structure of the system and its behaviour (Mehren et al., 2018), and it is characterised by the type of cause-effect relationships between the different parts, including monocausal, linear, and complex relationships. The mention of relationships between each of the dimensions in OH notion and the explicit reference to contagion were also specifically analysed to characterise the system PSTs were representing.

https://doi.org/10.33225/jbse/26.25.409

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

Table 2
Dimensions and Levels for Data Analysis

Dimension	Level	Description
ST-Comp	3	Components of the three OH spheres
	2	Components of two OH spheres
	1	Components of only one OH sphere
ST-OrgBeh	3	Complex relationships
	2	Linear relationships
	1	Monocausal relationships
	0	No cause-effect relationships
ST-Action	3	Complex relationships
	2	Linear relationships
	1	Monocausal relationships
	0	No cause-effect relationships
ST-InsV	1	Victim in first person
	0	No first-person reference
ST-InsC	1	Causes in first person
	0	No first-person reference
ST-InsA	1	Actions in first person
	0	No first-person reference

The levels for ST-Action are defined in the same way, but in relation to the effects of actions. As Uskola and Puig (2023) proposed, when participants explained their proposal of actions referring explicitly to causes (so implicitly to the effects of the action), they were considered at one level below the corresponding type of relationship. For example, in the activity A9-g, G7, and G3 both proposed the regulation of the use of antibiotics in livestock, but did it in a different way. G7 (ST-Action level 3) started the causal linear chain from the action:

Regulating the use of antibiotics in intensive livestock [a]. Regulating it [a], we prevent the food we consume from being saturated with antibiotics [b].	Monocausal a-b
It also prevents contaminated waste from affecting plant growth [c].	Link between chains (a: divergent branch)
Consequently, there will be fewer antibiotic resistant bacteria [d], thus increasing the effectiveness of antibiotics in humans.	Linear a-b-d Linear a-c-d

Besides, G3 (ST-Action level 1) made a linear causal chain (which would correspond to level 2) but not starting from the action, but from the generation of the problem: 'Antibiotics administered to livestock to prevent disease or accelerate growth [a] can lead to resistant bacteria [b], which can then reach humans through the food chain [c]. To prevent this, it is essential to promote the responsible use of antibiotics in livestock farming and establish strict controls.'

ST-Ins addresses the 'inside the system' perspective (Hipkins, 2021), that is, seeing oneself as a cause of the problem, as a victim, and as an agent of change. It was analysed based on the use of the first person (Granit-Dgani et al., 2017; Sass et al., 2021). All responses were coded by two researchers independently and discussed until reaching a consensus. This process was carried out in two phases. The first phase covered one-third of the sample, with a degree of agreement ranging from 75% (ST-Action) to 85% (identification of elements and relationships). Discussion of the points of disagreement led to clarification of the categorisation. The degree of agreement for the analysis of the rest of the sample was greater than 90% for all dimensions.

To address RQ1, individual written answers to individual activities A1-i and A11-i were taken into account. Specifically Q1 ('What is AMR? Explain in your own words how it occurs.'), Q2 ('Do you think that only people that take antibiotics can suffer AMR? That is, do you think that someone who does not take antibiotics will never suffer

https://doi.org/10.33225/jbse/26.25.409

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

from AMR? Explain.'), Q3 ('Explain all the processes that can occur so that a person suffers from AMR.') were analysed to characterise ST-Comp and ST-OrgBeh and ST-Ins, and Q4d ('Do you think that wearing a mask is related to AMR? Explain.') was used to characterise ST-Action. The results show the highest level found in each case. Regarding the statistical analysis, the Wilcoxon signed-rank test was used for comparing initial and final scores. SPSS v27 was used for non-parametric analyses to calculate *p* values. Then, given that multiple hypothesis tests were performed, the Holm-Bonferroni procedure was executed, and the Holm-Bonferroni adjusted *p* values were calculated (Aickin & Gensler, 1996). In addition, effect sizes ($r = Z/\sqrt{N}$) were calculated for each contrast, where Z is the standardized Wilcoxon signed-rank test statistic and N, the total sample size. The values of r can be interpreted as small effect ($\geq .10$), medium effect ($\geq .30$), or large effect ($\geq .50$) (Fritz et al., 2012). Lastly, confidence intervals for r were calculated using Fisher's Z transform (Jané et al., 2024).

To address RQ2, the ST showed during the sequence of activities (A6-g and A7-g for ST-Comp and ST-OrgBeh; A9-g for ST-Action) was also analysed. In the case of the analysis of the mind maps in A7-g, it was considered that an arrow between components indicated a relationship between them, but that it only indicated a causal relationship when the transmission of bacteria and/or antibiotics was explicitly indicated. Figure 1 shows the mind maps created by groups G1, G3, and G6 as examples. Unlike those of G3 and G6, the mind map of G1 does not explicitly depict bacterial transmission; it depicts only the administration of antibiotics to humans and animals. Therefore, it has been categorized as representing various interrelationships between Animals, Humans, and Environment, but the causal relationships do not extend beyond the monocausal category (level 1). In contrast, the mind maps of groups G3 and G6 represent chains of bacterial transmission, and these chains are connected through divergent and convergent branches, thus categorizing them at level 3.

Figure 1

Mind Maps Created by Groups

a) G1 b) G3 c) G6

Research Results

AMR as an OH Problem at Initial and Final Moments

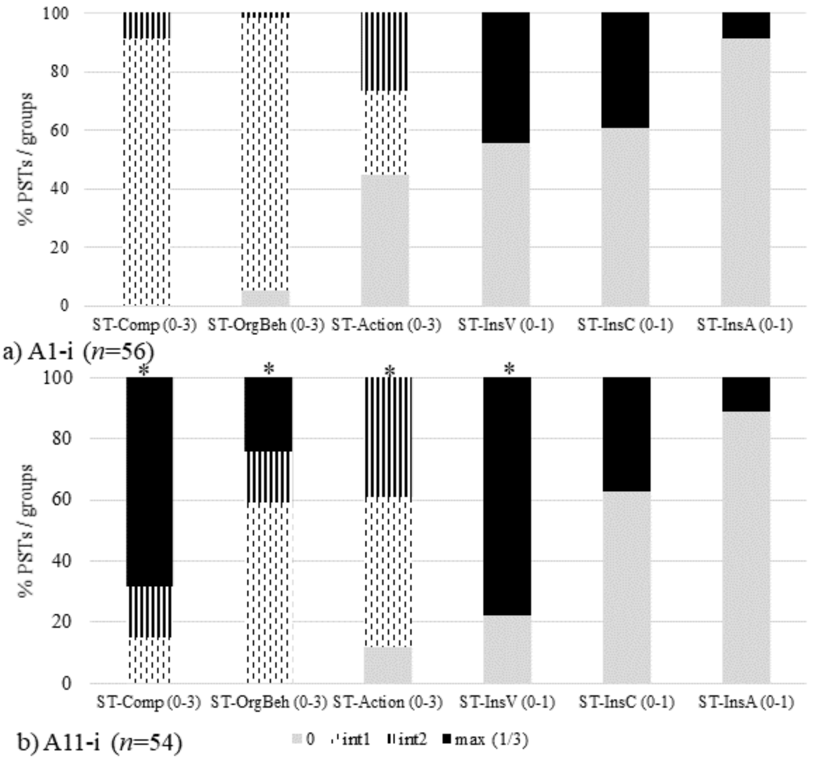
Figure 2 shows the percentage of PSTs at each level of each dimension of the ST analysed at the initial and final moments.

https://doi.org/10.33225/jbse/26.25.409

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

Figure 2

Frequency of PSTs at Each Level and ST Dimension at Initial and Final Moments

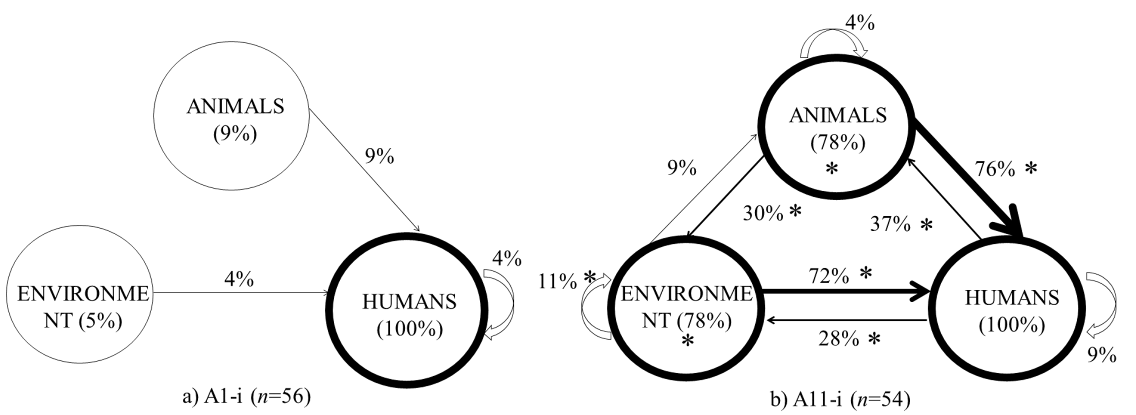


Note. Grey colour represents level 0, and black the highest level for each dimension. The stripped patterns represent intermediate levels. Stars above bars indicate a significant (p-value < .01) difference between initial and final results.

In the case of ST-Comp and ST-OrgBeh, the results show that the PSTs represented the AMR problem more in line with a complex system with OH vision at the end of the sequence than at the beginning. Initially, only 9% related the problem to Animals and/or Environment, while at the end of the sequence, 15% limited themselves to focusing the problem on Humans. When analysing the type of relationships between the three OH elements, the results shown in Figure 3 were found.

Figure 3

Frequency of PSTs that Referred to OH Elements and Relationships at Initial and Final Moments



Note. Stars indicate a significant (p-value < .01) difference between initial and final results.

https://doi.org/10.33225/jbse/26.25.409

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

As shown in Figure 3, at the end of the sequence, more than 75% PSTs referred to all elements and to all types of relationships between them. At the beginning, only a few relationships (all involving Humans) were mentioned; but at the end, although the relationships from Animals and the Environment to Humans were most mentioned (more than 70%), all were mentioned, with those not involving Humans being particularly noteworthy. Table 3 shows the significant differences and the effect size of the various elements and interactions between them.

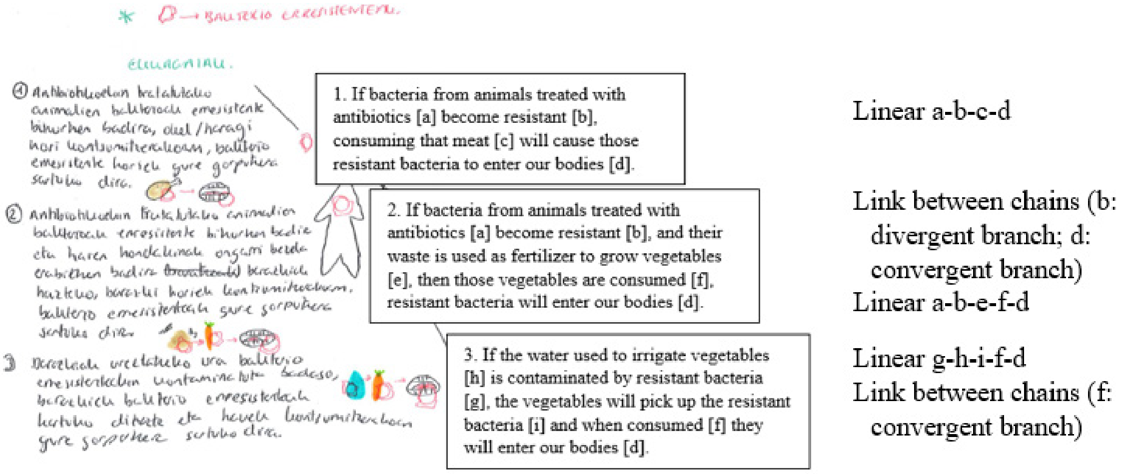
Table 3
Statistical Differences Between Initial and Final Scores for OH Elements and Interactions

OH element/Interaction	*Z*	*p*	Holm-adjusted *p*	*r*	95% CI for *r*
Humans	0.000	n.s.	1	.000	[–.268, .268]
Animals	6.083	< .001	.012	.828	[.720, .897]
Environment	6.091	< .001	.012	.829	[.721, .897]
Humans - Humans	1.134	n.s.	1	.154	[–.118, .405]
Humans - Environment	3.873	< .001	.012	.527	[.302, .697]
Humans - Animals	4.472	< .001	.009	.609	[.407, .754]
Animals - Animals	1.414	n.s.	1	.192	[–.079, .438]
Animals - Environment	4.000	< .001	.012	.544	[.324, .709]
Animals - Humans	6.000	< .001	.012	.816	[.702, .890]
Environment - Environment	2.449	n.s.	.155	.318	[.055, .540]
Environment - Animals	2.236	n.s.	.252	.304	[.040, .529]
Environment - Humans	6.083	< .001	.012	.828	[.720, .897]

Note. n.s.: not significant.

The possibility of contagion was explicitly stated by 28.6% and 74.1% of PSTs in A1-i and A11-i, respectively ($p < .001$, $r = .611$, 95% CI: [.410, .755]). Furthermore, the type of causal relationships established was more complex at the end of the sequence, with all PSTs establishing some type of relationship between elements, 50% being monocausal (level 1) and the other 50% being linear or complex (levels 2 and 3). Figure 4 shows part of the representation made by PST9.4 in A11-i and the corresponding coding.

Figure 4
Representation Made by PST9.4 in A11-i



https://doi.org/10.33225/jbse/26.25.409

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

With regard to ST-Action, the results show an evolution at the end of the sequence, as the percentage of PSTs that did not establish any relationship decreased (from an initial 44.6% to a final 11.8%) and the percentage of PSTs at level 2 corresponding to linear relationships increased (from an initial 26.8% to a final 39.2%). However, no PST reached the level of complex relationships (level 3) in the final activity A11-i.

Regarding the dimensions related to seeing oneself 'inside the system,' the results in Figure 2 show that PSTs progressed in all three, albeit unevenly, such that at the end, 77.8%, 37%, and 11.1% of PSTs saw themselves as victims, causes, or possible agents of change in the problem, respectively. Table 4 shows the statistically significant differences and corresponding effect sizes in the dimensions of the ST.

Table 4
Statistical Differences Between Initial and Final Scores for ST Dimensions

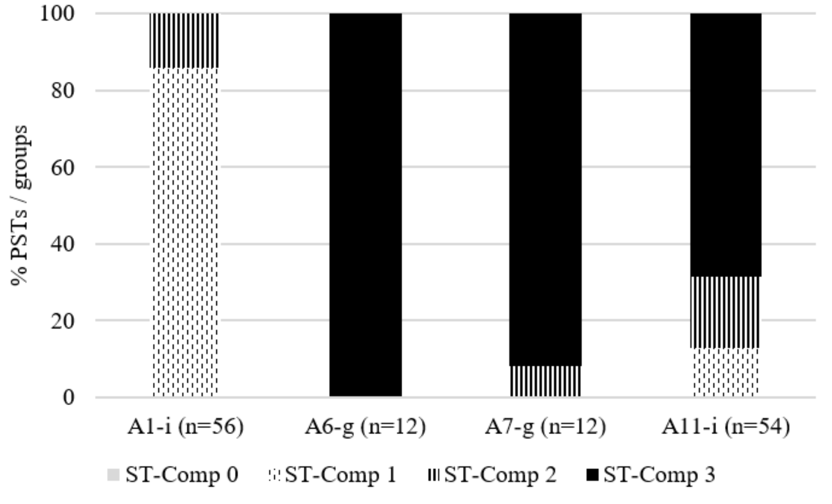
ST dimension	Z	*p*	*r*	95% CI for *r*
ST-Comp	6.184	< .001	.841	[.741, .905]
ST-OrgBeh	4.419	< .001	.601	[.398, .749]
ST-Action	3.384	< .001	.460	[.220, .648]
ST-InsV	3.157	< .001	.429	[.183, .625]
ST-InsC	0.426	n.s.	.058	[–.213, .321]
ST-InsA	0.378	n.s.	.051	[–.219, .315]

Note. n.s.: not significant

OH Dimensions and Interrelationships During the Modelling Sequence

Figure 5 shows the percentage of PSTs and/or groups at each level of ST-Comp in the activities carried out throughout the sequence. As shown in Figure 5, the change in trend in the OH perspective of the problem, in terms of taking into account the diversity of components, occurred in activity A6-g and continued until the end. Even in activity A9-g, in which the groups were limited to proposing three actions, two-thirds of the groups mentioned the three OH dimensions, and only one group limited itself to the human dimension.

Figure 5
Frequency of PSTs and/or Groups in ST-Comp Levels During the Sequence



Delving deeper into this analysis, Figure 6 and Figure 7 show the percentage of PSTs and groups that referred to each of the elements and each of the relationships between them, respectively. In relation to interrelationships,

https://doi.org/10.33225/jbse/26.25.409

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the mention of the possibility of contagion was also higher in intermediate activities (91.7% and 83.3% of groups in A6-g and A7-g, respectively).

Figure 6

Frequency of PSTs and/or Groups Referring to Elements During the Sequence

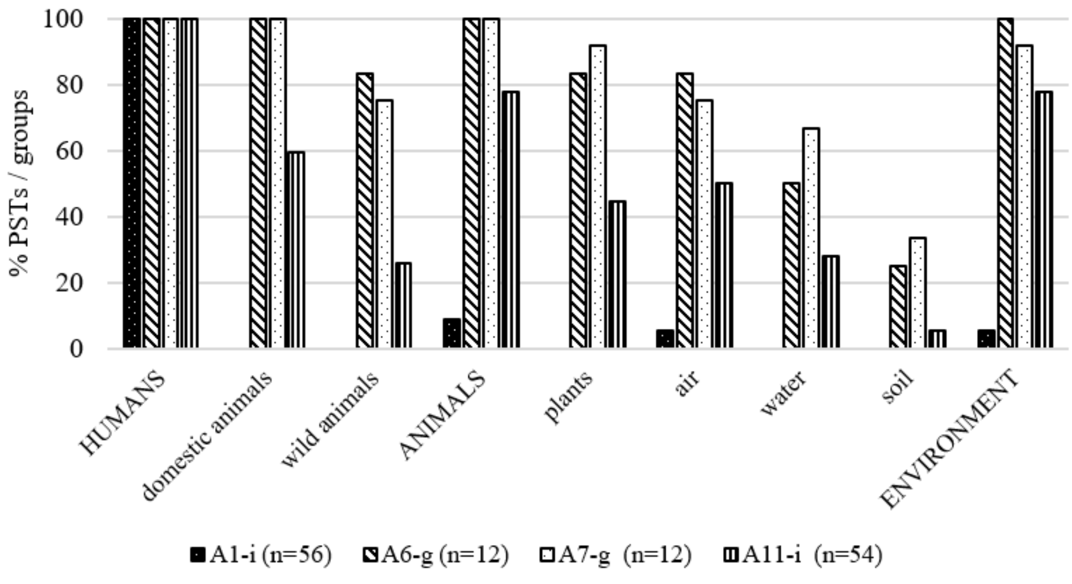
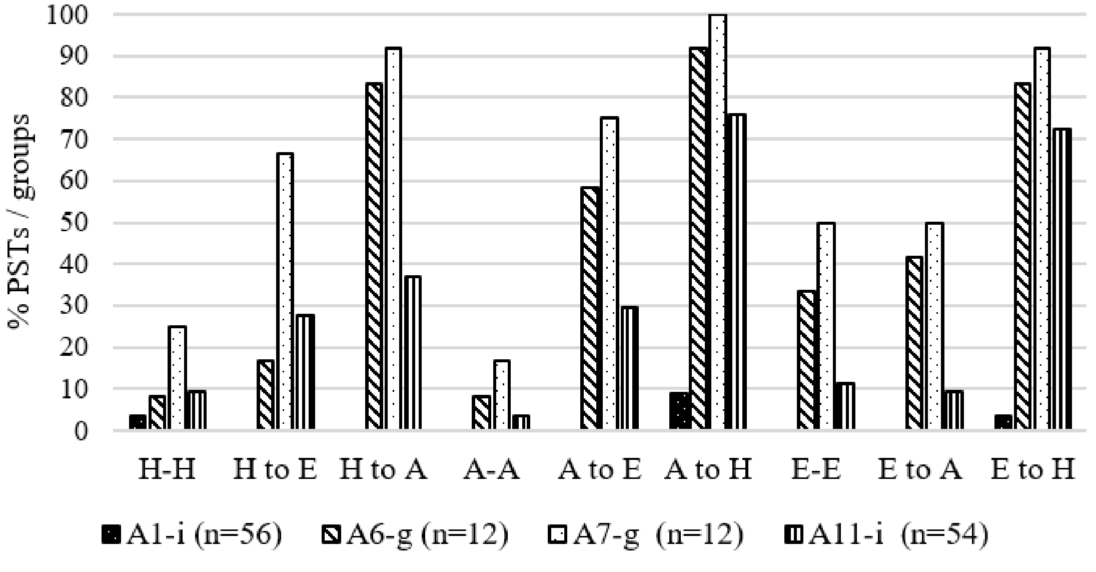


Figure 7

Frequency of PSTs and/or Groups Referring to Relationships during the Sequence



Note. H: Humans; A: Animals; E: Environment

As can be seen in Figures 6 and 7, intermediate activities facilitated the mention of non-human elements, reaching the highest frequency of PSTs. The results shown in Figure 7 reflect that this was more pronounced in A7-g, given that all interactions were represented by more groups in this activity than in any other. In the mind maps shown in Figure 1, both the diversity of elements and relationships, as well as the complexity of the latter in the case of G3 and G6, can be observed.

https://doi.org/10.33225/jbse/26.25.409

ISSN 1648-3898 /Print/
ISSN 2538-7138 /Online/

The results of the evolution of the groups also reflect the key role of activity A7-g. Thus, in the case of various elements and interactions mentioned in A6-g but not in A7-g, they were not mentioned by any member of the group in A11-i: water (G1), wild animals (G2, G5), soil (G9), Environment (G12), Environment to Animals (G2, G7, G9), Animals-Animals (G5), Humans to Animals (G6, G11). Conversely, various elements and interactions that were represented for the first time in A7-g were mentioned in A11-i: air (G5), plants (G7), water (G8), Environment-Environment (G1), Humans to Environment (G1, G3, G4, G7, G9, G10), Environment to Animals (G3), Animals-Animals (G6), Environment to Humans (G7), Humans-Humans (G10, G12), Animals to Humans (G11), Humans to Animals (G12).

Complexity of the Interrelationships During the Modelling Sequence

Figure 8 shows the percentage of PSTs and/or groups at each level of ST-OrgBeh in the activities carried out throughout the sequence.

Figure 8
Frequency of PSTs and/or Groups in ST-OrgBeh Levels During the Sequence

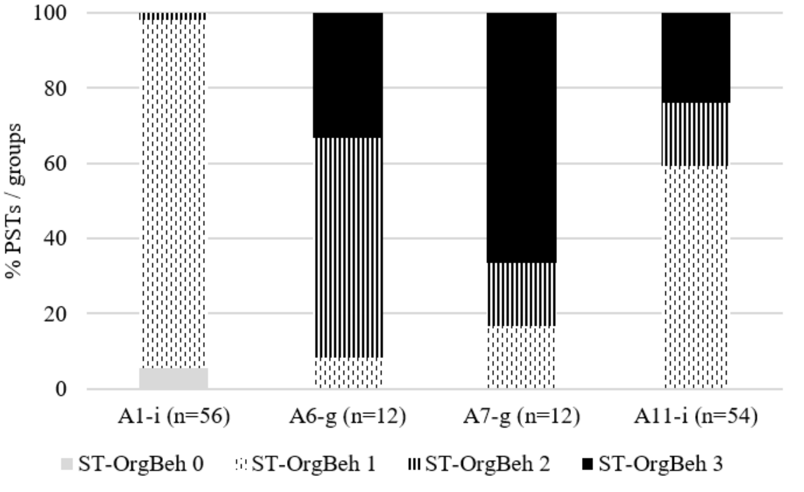


Figure 8 shows that the level of complexity of causal reasoning demonstrated in group activities was higher than at the initial stage, and higher in A7-g than in A6-g. Indeed, throughout these activities, most groups demonstrated linear or more complex forms of reasoning, and in some cases (40%), this was still evident at the end of the sequence. The trajectory followed by each group is shown in Figure 9.

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ISSN 1648–3898 /Print/
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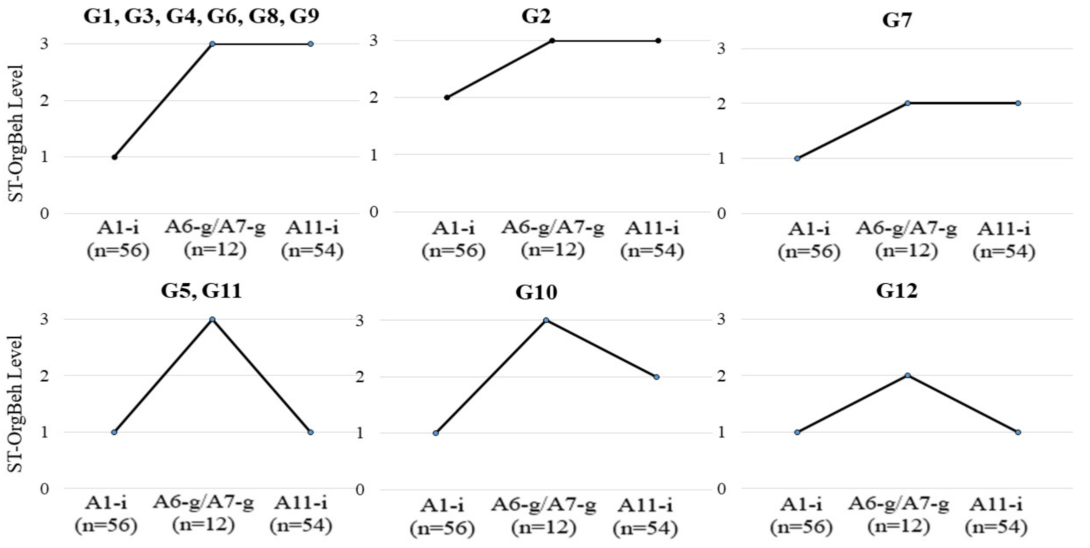
Figure 9
Maximum Level Achieved by the Groups During the Sequence



All groups demonstrated more complex reasoning in some of the intermediate activities (A6-g, A7-g) than any of their members had initially demonstrated (A1-i). In seven of the 10 groups that had reached level 3 in A6-g or A7-g, at least one member of the group reached that level of performance in A11-i. In the case of group G7, which had reached level 2 in A6-g and A7-g, this was the maximum level achieved by its members in A11-i. In summary, in eight of the 12 groups, at least one of their members showed in the final activity the level achieved in the intermediate activities.

Regarding the differences in performance in A6-g and A7-g, six groups (G2, G3, G4, G5, G10, G11) showed a higher level of complexity in A7-g than in A6-g, while two groups (G1, G8) showed greater complexity in A6-g, and four (G6, G7, G9, G12) showed the same level in both activities. More precisely, in the six groups that showed greater complexity in A7-g than in A6-g and that in the final activity A11-i maintained that level, the individuals that managed to maintain the level shown in A7-g were 13 out of 26: one in each G2 and G3, two in each G4 and G7, three in G9, and four in G6. It is noteworthy that several participants produced individual representations in A11-i that reflected the group representation made in A7-g four weeks earlier. As an example, Figure 10 shows the responses of two of the PSTs from groups G3 and G6, whose mind maps are shown in Figure 1.

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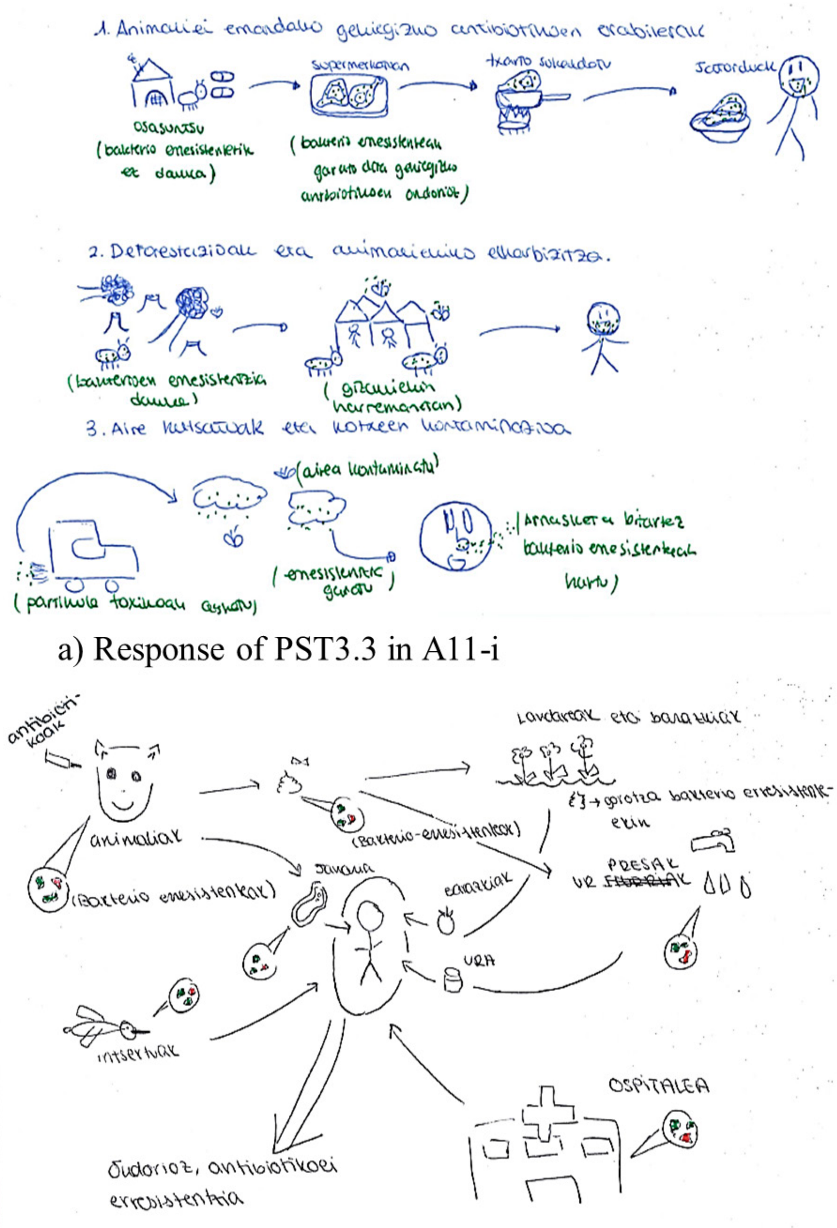
Figure 10
Responses in A11-i by (a) PST3.3 and (b) PST6.2



a) Response of PST3.3 in A11-i

b) Response of PST6.2 in A11-i

PST3.3 in A11-i (Figure 10) drew several of the elements and relationships that appeared in her group mind map (Figure 1). For example, the transmission of resistant bacteria from domestic animals to humans through food, deforestation, or the emission of particles from cars into the air, and their contribution to the transmission of resistant bacteria. PST6.2 also represented elements and relationships in her final activity (Figure 10) in a similar way to how her group had done in A7-g (Figure 1). Thus, she drew a similar mind map with many of the elements (hospital, domestic animals, mosquitoes as vectors, crops) and established similar complex relationships, depicting the various routes of transmission of resistant bacteria. Figure 11 shows the percentage of PSTs and/or groups at each level in ST-Action throughout the sequence.

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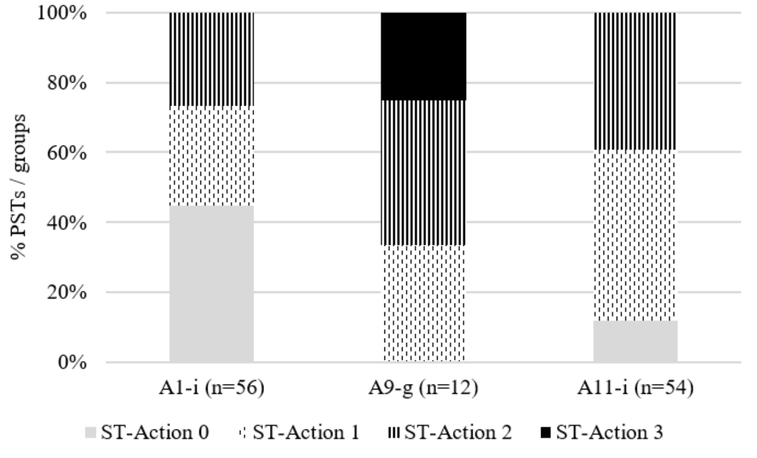
ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

Figure 11
Frequency of PSTs and/or Groups in ST-Action Levels During the Sequence



As shown in Figure 11, all groups achieved level 1 in at least one of the three proposed actions (A9-g), and three of them achieved level 3. Below is the G4 group's proposal to use public transport:

By using public transport [a], the emission of particles into the air is reduced [b], thereby we prevent resistant bacteria from being transported with the particles [c]. In other words, we avoid absorbing bacteria through inhalation [d].	Linear a-b-c-d
On the other hand, public transport [a] pollutes less compared to private cars [e].	Monocausal a-e Link between chains (a: divergent branch)
Air pollution [e] affects health, increasing respiratory infections [f], which are often treated with antibiotics [g]. If these antibiotics are misused, the possibility of developing resistance [h] increases.	Linear e-f-g-h (from cause)

As can be seen, the chain of reasoning that began in a-e was considered monocausal and separate from the linear e-f-g-h, since in the latter, the group modified its discourse and instead of reasoning from actions and their consequences ('pollution will decrease'), it did so from pollution as a cause. This was the case for 13 of the 36 actions proposed in A9-g and produced a decrease in ST-Action level from 2 to 1 for G3. No answer was penalised in A1-i and only one in A11-i: PST10.1´s response was penalised from ST-Action level 2 to 1.

The evolution of the groups throughout the sequence was quite irregular, in the sense that no patterns could be identified. Some groups maintained the same maximum level in all activities (G1, G2, G5, G6, G12), worsened in the intermediate activity (G8, G11), improved in the intermediate activity but not in the final activity (G4, G7, G9), and improved in both the intermediate and final activities (G3, G10).

'Being Inside the System' During the Modelling Sequence

Figure 12 shows the percentage of PSTs and/or groups that used the first person in the different activities, according to whether they referred to themselves as victims of the problem, causes, or possible agents of change.

https://doi.org/10.33225/jbse/26.25.409

ISSN 1648–3898 /Print/
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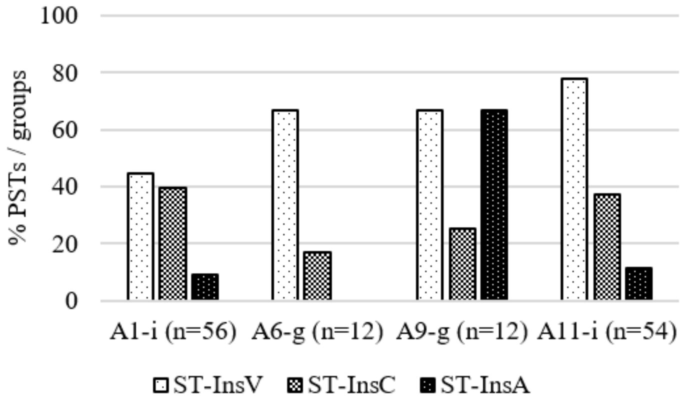
Figure 12
Frequency of PSTs and/or Groups at Level 1 in ST-Ins Dimensions During the Sequence



As shown in Figure 12, unlike the ST-Comp, ST-OrgBeh, and ST-Action dimensions, the groups did not make intermediate representations in which the ST-Ins dimension was reflected at a higher level than in the initial (A1-i) and final (A11-i) individual activities. The only exception was in the case of seeing themselves as agents of change in the action proposal activity A9-g, in which two-thirds of the groups did use the first person as agents of these actions, when this was the ST-Ins sub-dimension least present in both A1-i (8.9% of PSTs) and A11-i (11.1% of PSTs).

Discussion

This exploratory study has addressed the knowledge of trainee teachers on a global health problem, AMR, and how it fits in with the global OH vision (FAO et al., 2019) in which it should be considered (O'Neill, 2016; UNEP 2023; WHO, 2023), as well as how participating in a modelling sequence helps to develop such a vision. At the beginning, participants demonstrated an almost complete absence of a global perspective on the problem, with only a small number mentioning animals or the environment. These results are in line with previous studies in which participants have shown gaps in their global view of human health problems, such as pandemics (Uskola & Puig, 2023) or AMR (Martínez-Pena et al., 2024). Nevertheless, almost 70% of secondary school students stated that it was possible for antibiotic-resistant bacteria to be transmitted through contact with live animals, food or water when asked directly (Robredo & Torres, 2021). This indicates that when asked directly about the possibility of transmission, students may give answers that suggest they have integrated the transmission perspective into their understanding of the AMR problem, but when the question requires them to apply this perspective, they fail to do so, demonstrating that they have not integrated it (Kilstadius & Gericke, 2017). Therefore, it is unlikely that they considered it when making decisions. In fact, none of the proposed actions to minimise the problem included in the systematic review of studies by McCullough et al. (2016) incorporated this perspective, despite the recommendations in the O'Neill report (2016) emphasising it.

Moreover, the low initial levels of the various dimensions of ST analysed placed PSTs at novice levels (Hmelo-Silver & Pfeffer, 2004), and were lower than those shown by younger students in more limited contexts (Mambrey et al., 2022; Snapir et al., 2017). These findings align with the results of the study conducted by Palmberg et al. (2017), demonstrating that the demand for ST is higher in holistic contexts, as required by the OH vision.

The results suggest that the activities implemented may have contributed to a shift in this situation. Thus, at the end of the sequence, 78% of PSTs referred to all OH components, as well as to all the possible interactions between them. Furthermore, they established interrelationships between elements through complex articulations of the cause-effect relationships between them. They explained the interrelationships through mechanisms they had not initially described, such as the possibilities of contagion between animals and from animals to humans (Kilstadius & Gericke, 2017). This focus on mechanisms and phenomena, and not just structural components, is considered the highest level of ST (Hmelo-Silver et al., 2017) and is what defines the way experts think about a system compared to novices (Hmelo-Silver & Pfeffer, 2004).

https://doi.org/10.33225/jbse/26.25.409

ISSN 1648-3898 /Print/
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In the final situation, 40% of PSTs established cause-effect relationships of linear and complex type when describing and explaining AMR. Formulating complex causal relationships is a demanding skill, in which students show difficulties (Levrini et al., 2021; Mambrey et al., 2022), and although the results show progress, they confirm the need to focus on developing these skills. PSTs showed less progress in establishing cause-effect relationships to explain the consequences of possible actions to be taken, i.e., when thinking prospectively. This greater difficulty in thinking prospectively can be related to the characterisation of the dimensions of ST by Mehren et al. (2018), according to which prospective thinking corresponds to the application of knowledge about the system.

On the other hand, proposing actions that modify the system, in this case mitigating a global health problem such as AMR, is linked to agency, the capacity to take responsibility and make decisions to realise the desired future (Levrini et al., 2021), which is related to the ability to see oneself as part of the system (Hipkins, 2021). In general, this dimension of ST showed no notable progress, with the sole exception of an increased tendency to perceive oneself as a victim. In the final situation, almost 80% of PSTs saw themselves as direct victims of AMR, which is important as a first step in taking action. Indeed, in their revision, Maiella et al. (2020) reported that, with exceptions, studies generally indicated that people exhibited pro-environmental behaviours toward climate change when they perceived the problem as closer. Seeing oneself as a victim can be an indicator of that closeness or short psychological distance. Related to this, previous studies, i.e., (Jornet, 2025; Khazem, 2025; Tvinnereim et al., 2020) have shown concern that many students do not see themselves as victims of global problems such as climate change.

The activity of proposing actions stood out due to the high number of groups that showed a sense of being inside the system in the sense of being agents of change. However, it seems that the contribution of the intermediate activity was not reflected in the results. Perhaps this is due to the wording of the question (Uskola & Puig, 2023), since in the intermediate activity it was they who proposed the actions, while in the final activity, they evaluated one that was proposed to them. This issue would need further research, and it would be preferable for requests for proposals for action from students to be formulated in such a way as to encourage them to make personal commitments. However, it may also be due to a lack of agency development, which would be supported by the low index indicating a sense of being a cause of the problem. This is worrying. Seeing themselves as victims is a first step towards becoming aware of the problem, but in order to take action, they need to see themselves as something more: as agents of change (Levrini et al., 2021). It will therefore be necessary to investigate how to achieve this goal in future teaching sequences. Several educational interventions have been carried out aimed at reducing the aforementioned psychological distance associated with climate change, and in several of them, the development of narratives to visualise possible future scenarios has been used with promising results (Liu, 2024; Reynante et al., 2025). Futures thinking (Levrini et al., 2021) is thus an important issue to be addressed more in future interventions.

In the case of dimensions related to understanding the system (Mehren et al., 2018), i.e., identifying elements and their interrelationships and establishing complex cause-effect relationships, the intermediate activities of reading texts, writing ideas, and creating mind maps contributed to their development. In fact, it was observed that the groups performed at the highest levels in these dimensions in the intermediate activities and that, in some cases, their members recalled what they had done in the intermediate activities when responding to the final individual activity. As for the contribution of each activity, although this study is limited and more specific studies should be carried out to address the contribution of other possible variables, the performance results of each group point to a contribution from the group creation of the mind maps, especially in those aspects of greater complexity, such as interrelationships and specifically cause-effect relationships. That is, it can be hypothesised that, among other possible factors, representing the ideas they had obtained in texts in the form of a mind map, in addition to writing them down, helped them to establish new relationships between components and to make these relationships more complex, with chains of arrows, divergent and convergent branches, and feedback loops. At the individual level, a few PSTs appeared to have begun integrating this complexity, suggesting that multimodal representation (Prain & Tytler, 2021), and especially the mind map, may have supported their understanding of the system. This result supports others that promote making representations in science (Prain & Tytler, 2012; Tytler et al., 2023), specifically mind maps as a tool for the development of ST (Ben-Zvi-Assaraf & Knippels, 2022; Hmelo-Silver et al., 2017; Tripto et al., 2013), providing evidence of their contribution in relation to specific dimensions of ST in a complex healthcare system. The benefit of using various modes of representation can also be concluded from the contrast of the aforementioned

https://doi.org/10.33225/jbse/26.25.409

ISSN 1648-3898 /Print/
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results with the results obtained in the prospective dimension. Although the groups showed the highest level in the activity of proposing actions, the individual results in the final activity and those of the groups' evolution do not lead to the conclusion that the PSTs had integrated that dimension of the ST. That is, it seems that the intermediate activity in which they represented their ideas in written text mode was not sufficient; making another representation, may have facilitated students to organise, integrate, and deepen their understanding (Prain & Tytler, 2021). The results point to the interest of using multimodal representations, including mind maps in science education that seeks to train citizens who understand the complex health problems and can act on them (OECD, 2018).

Conclusions, Limitations, and Implications

This study explored how the various representations of a system throughout a modelling sequence may have facilitated the development of systems thinking in a group of PSTs, in the context of a complex health problem, AMR. It has to be taken into account that the sample was small and that, since the research was mainly qualitative, it was not the aim of this exploratory study to generalize its conclusions, but to obtain the most authentic picture possible of the learning process in a group of participants. It was found that PSTs did not initially consider AMR as a systemic global health problem. It was after participating in the modelling activities that this notion changed, and they could construct an AMR notion that considered the diversity of elements and interactions. PSTs, after participating in the sequence, explained the various ways in which AMR can affect a person, articulating complex chains of reasoning. They were also able to propose actions to address the problem, although they did not articulate them in such a complex way. It may be said that the results suggest that the use of diverse modes of representation, the multimodality facilitated the development of the mentioned complex articulations. It is not possible to attribute a causal relationship between the use of multimodality and complex articulations in reasoning. This would require in-depth research in varied and multiple contexts, including recordings of discussions, but in this study, multimodality, in the context of the sequence proposed, seems to have played an important role, taking into account all the limitations. It must be acknowledged that the sample was small and, as in all research, other factors may have had an influence on the final results. It has been found that some questions should be phrased differently to make it easier for students to focus their answers more appropriately, or that the indicators chosen to define the levels could be expanded to better capture the corresponding performance, for example, in the case of agency. Other hypothetical factors have been addressed. For example, it is known that the maturation of the participants throughout the study can influence the results; however, in this study, the participants had an average age of 21, and a few weeks may have had little effect on their maturity. Another factor is the Hawthorne effect, the modification of participants' behaviour or performance because they are being observed. In this case, the participants were not taking part in a study, but in a classroom activity with their teacher. It was only afterwards that they were asked for consent, so that the tasks performed by them were analysed for the study, and the context in which they carried out the activities was a natural classroom context.

These results imply that students do not naturally express complex perspectives on the problems they face, and that this applies to PSTs as well. They also imply that the development of the needed ST skills can be facilitated by the use of modelling strategies that involve diverse modes of representation. Nevertheless, the findings indicate that it has to be studied how to foster agency. In this sense, the agency should be characterised more broadly and analysed accordingly. On the other hand, activities that include making narratives to visualise possible future scenarios, such as role-playing, may be good candidates to foster it. Recommendations for future interventions in science education aimed at developing the ST dimensions addressed in this paper in relation to AMR would be:

- Give readings that address the diversity of elements and relationships that give rise to AMR as an OH problem
- Formulate the prompt 'Represent all the ways I might encounter AMR' to organise the information contained in the readings that aim to broaden the vision of the problem to an OH vision, both to write down ideas and to represent them in other ways
- Request more than one type of representation, for example, both written and visual representation
- Give explicit instructions for representing the transmission of bacteria or antibiotics in mind maps or other visual representations

https://doi.org/10.33225/jbse/26.25.409

ISSN 1648–3898 /Print/
ISSN 2538–7138 /Online/

- Use strategies that can build agency (roleplay, case clinics, futures narratives)
- Encourage the formulation of first-person commitments when requesting proposals for action

It is necessary to conduct further research to identify and characterise the contribution of these and other strategies that facilitate the development of ST skills. It can be helpful to use such strategies to train future teachers so that they are better equipped to train their future students, enabling them to understand the complex global health problems they will face and to take action to prevent and minimise them.

Acknowledgements

This study was funded by MCIN/AEI/10.13039/501100011033/ FEDER (research project PID2022–137010OB–I00).

Declaration of Interest

The authors declare no competing interest.

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Received: *January 30, 2026* Revised: *March 02, 2026* Accepted: *April 04, 2026*

Cite as: Uskola, A., & Gardeazabal, H. (2026). Multimodal representations for developing preservice teachers´ systems thinking for addressing complex health issues. *Journal of Baltic Science Education*, *25*(2), 409–430. https://doi.org/10.33225/jbse/26.25.409

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